Lecture 7

Synchrotron Storage Ring RF Systems

PART II

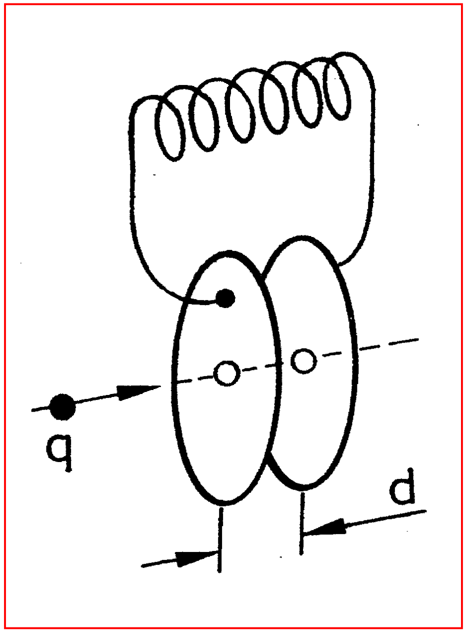
November 21, 2002

The RF Cavity

- E-field is induced across gap, similar to a parallel plate capacitor in a CRT.
- Each time particle traverses this gap, it sees a potential difference and is accelerated.
- As APS Booster is circular, the particles traverse through the cavity many times, until they reach the desired 7GeV energy.

RF Cavity

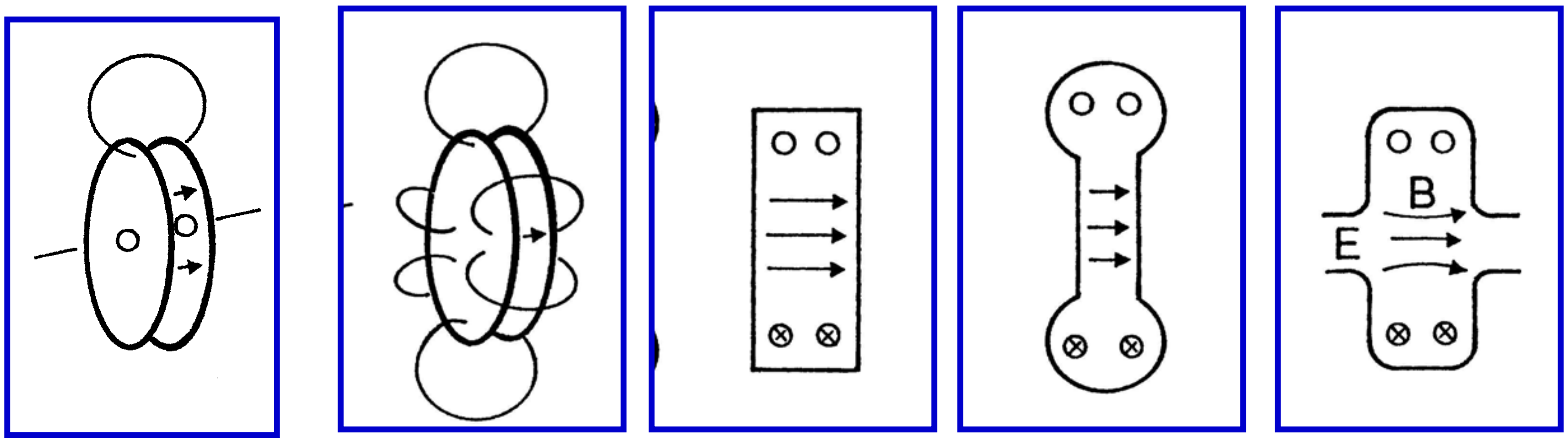
- RF cavity looks like a tuned L-C circuit to the PSU.



- $w_o = \sqrt{1/LC}$
- d adjusted to particles velocity $v = \beta c$, and its resonant frequency w_o.
- E-field accelerates particle during its transit time.

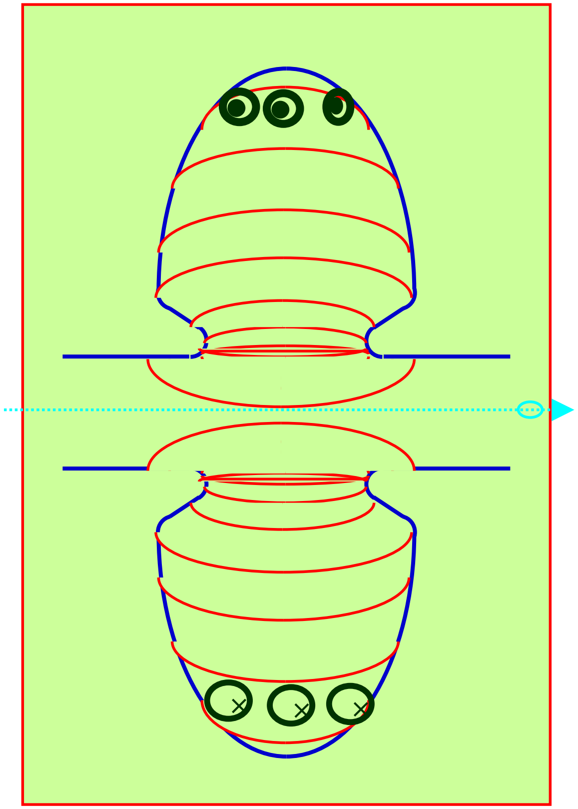
RF Cavity

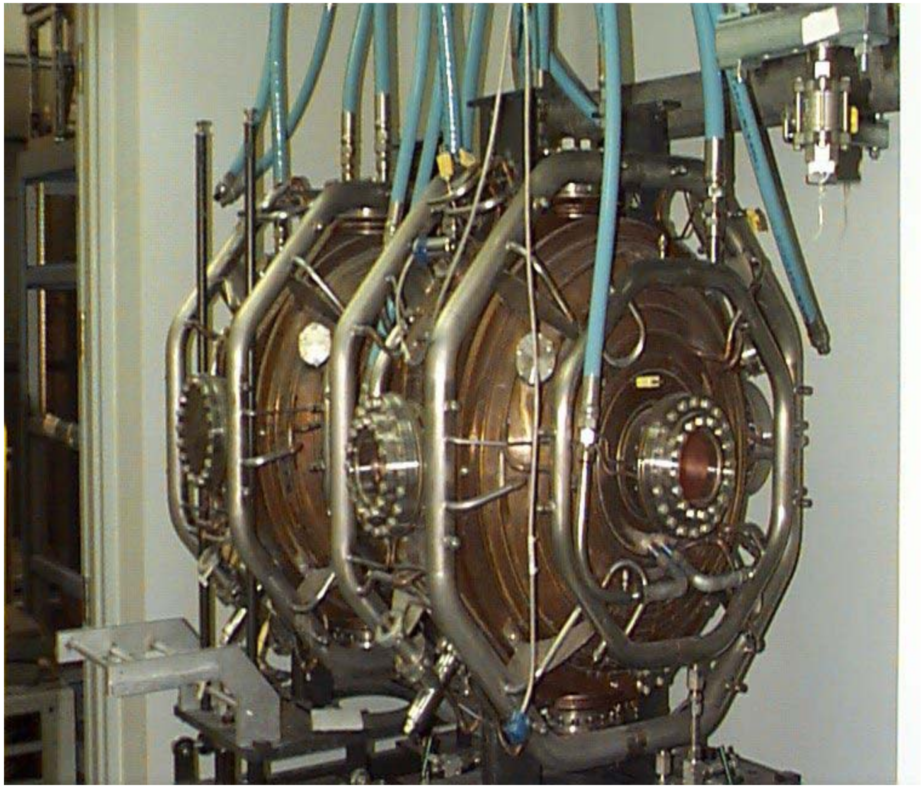
- Metamorphosis of L-C circuit into an accelerating cavity:



- H-field reaches maximum at cavity equator.

APS SR RF Cavity





RF Cavity

- Cavity has a huge natural inductance L.
- By tuning the capacitance C to cancel L, a near pure resistance, often referred to as shunt resistance R_o, can be achieved.
- Only when the L and C cancel, maximum power is transferred to the cavity.

RF Bucket

- When beam is captured by the RF system, it is contained in an **RF Bucket**.
- Since the cavity is a resonating structure at a specific RF frequency, standing waves are generated within the structure.
- These standing wave "pockets" are the RF buckets.
- These buckets do not have to contain beam.

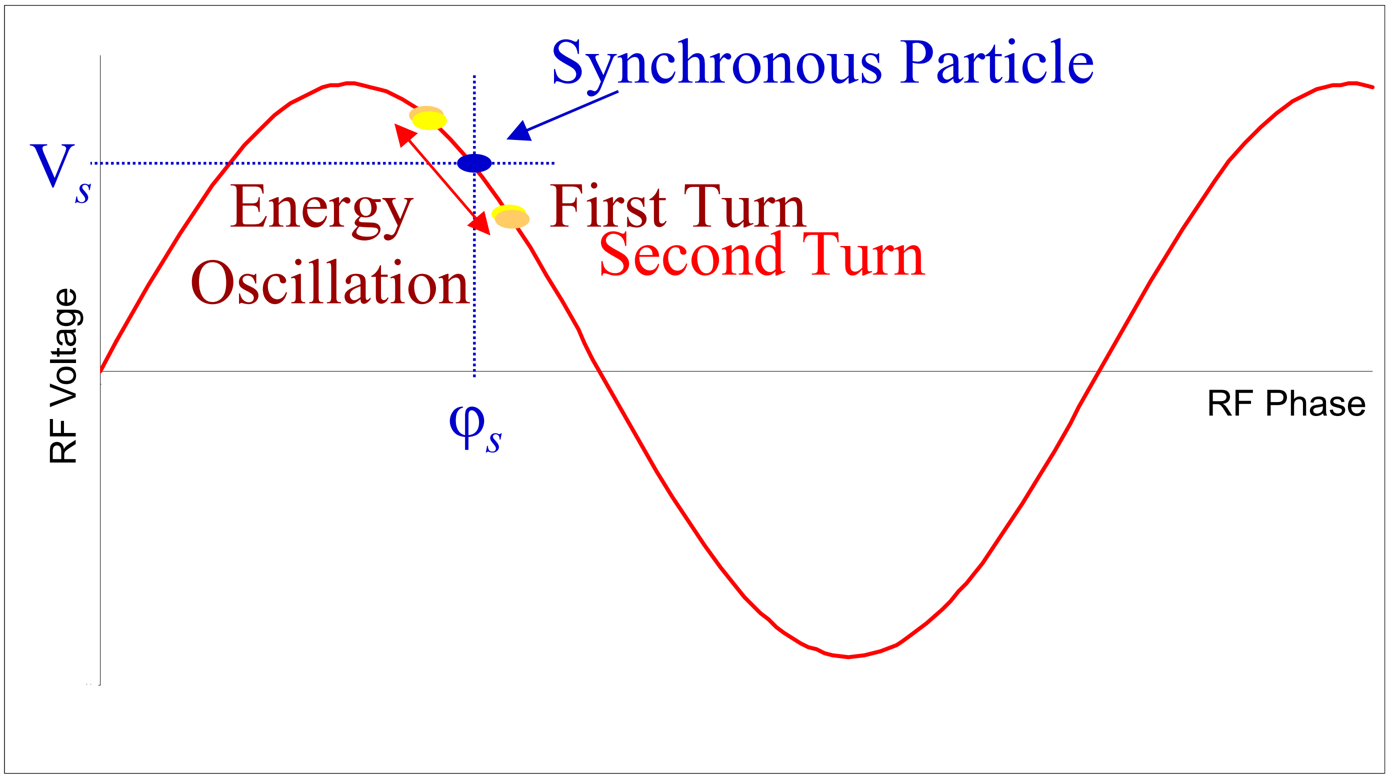
RF Bucket

- If the RF bucket contains beam, then the particles contained within the bucket is referred to as a bunch.
- Harmonic number (h) describes the number of bunches in an accelerator.
- For the APS:
  - h=1296 for the Storage Ring.
  - h=432 for the Booster.

Low Level RF (LLRF)

- LLRF provides the RF frequency used for acceleration.
- Also takes care of the correct phasing, so that the traversing bunches, through the cavity, see an accelerating voltage (V_{acc}).
- Consider a synchronous particle, which sees the same V_{acc} at each consecutive turn.

Low Level RF (LLRF)

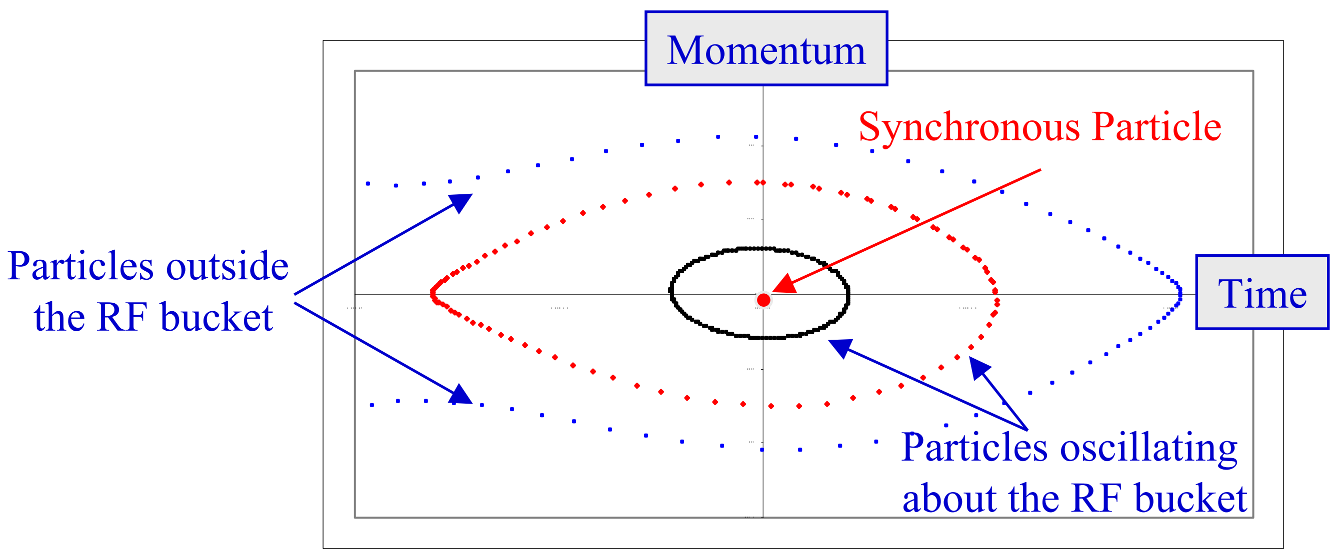


Synchrotron Oscillations

- This oscillation about the synchronous particle is termed; Synchrotron oscillation.
- Particles undergoing synchrotron oscillations will either have:
  - large enough energy/phase errors that they are lost by the RF.
  - they will continue with their synchrotron oscillations until they are damped.

Synchrotron Oscillations

- Synchrotron oscillations have the effect of spreading out the particles in the stable region of the RF bucket.
- Increasing the longitudinal emittance.



How Much RF Is Needed?

- RF must:
  - Provide the voltage to accelerate the Beam, providing a good lifetime and reasonable energy acceptance.
  - Replace the energy lost by the Beam due to synchrotron radiation.

Energy Loss due to Bending Magnets

Energy Loss/Turn,

$$\boxed{U_b = \frac{88.5 E_0^4}{\rho}}$$

where:

E_o = Beam Energy (GeV),

ρ = Magnet Bending Radius (m).

Energy Loss due to Insertion Devices

Energy Loss from ID/Turn,

$$\boxed{U_{id} = 0.633 E_o^{\,2} B^2 l}$$

where:

B = Field Strength (T),

E_o = Beam Energy (GeV),

l = length of the device (m).

Total Energy Loss

$$\boxed{U_o = U_b + U_{id}}$$

where:

U_o is the total Energy Loss / Turn

APS Example: U_b

- Storage Ring Energy = 7.0 GeV
- Magnet Bending Radius = 38.96 m

Therefore U_b = 5.45 MeV

APS Example: U_{id} Undulators

Storage Ring Energy	= 7.0 GeV
Undulator Field	= 0.85 T
Undulator Length	= 2.4 m
Therefore U_{id} from Undulator	= 54 keV
Max U_{id} from Undulators	= 1.25 MeV

APS Example: U_o

- U_b = 5.45 MeV/turn
- U_{id} Undulators = 1.25 MeV/turn

$$\boxed{U_o = 5.45+1.25 = 6.7 \text{ MeV/turn}}$$

APS Example: Power Losses

$$\text{Energy Loss} = U_o \times \mathrm{I_b}$$

- Energy Loss for 100 mA due to Bending Magnets is 545 kW.
- Energy Loss for 100 mA due to Insertion Devices is 125 kW.
- Total Energy loss to be made up by the RF system is 670 kW.

Acceleration Voltage

The voltage required to accelerate the beam is

$$V_p = KU_o$$

where K is the Overvoltage

Overvoltage

K is determined by :

- the Quantum Lifetime, T_q
- the Energy Acceptance, E_{max}/E_o
- the TOUSCHEK Lifetime, T_t

APS Example: RF Required

- For the **APS** $K \propto 1.42$,
  - $\therefore V_p = 9.5$ MV, assuming the Effective Shunt Impedance of each cavity is 5.6 MΩ.
- The power to accelerate the beam is 642 kW

Making the total RF power for the APS 1.3 MW

Why use Wave guide?

- Two transmission line options:
  - – Coaxial.
  - – Wave guide.
- Coaxial transmission line:
  - – has no cut-off frequency in its normal TEM mode, and can be used down to DC.
  - – power handling capabilities tail off at high frequency.

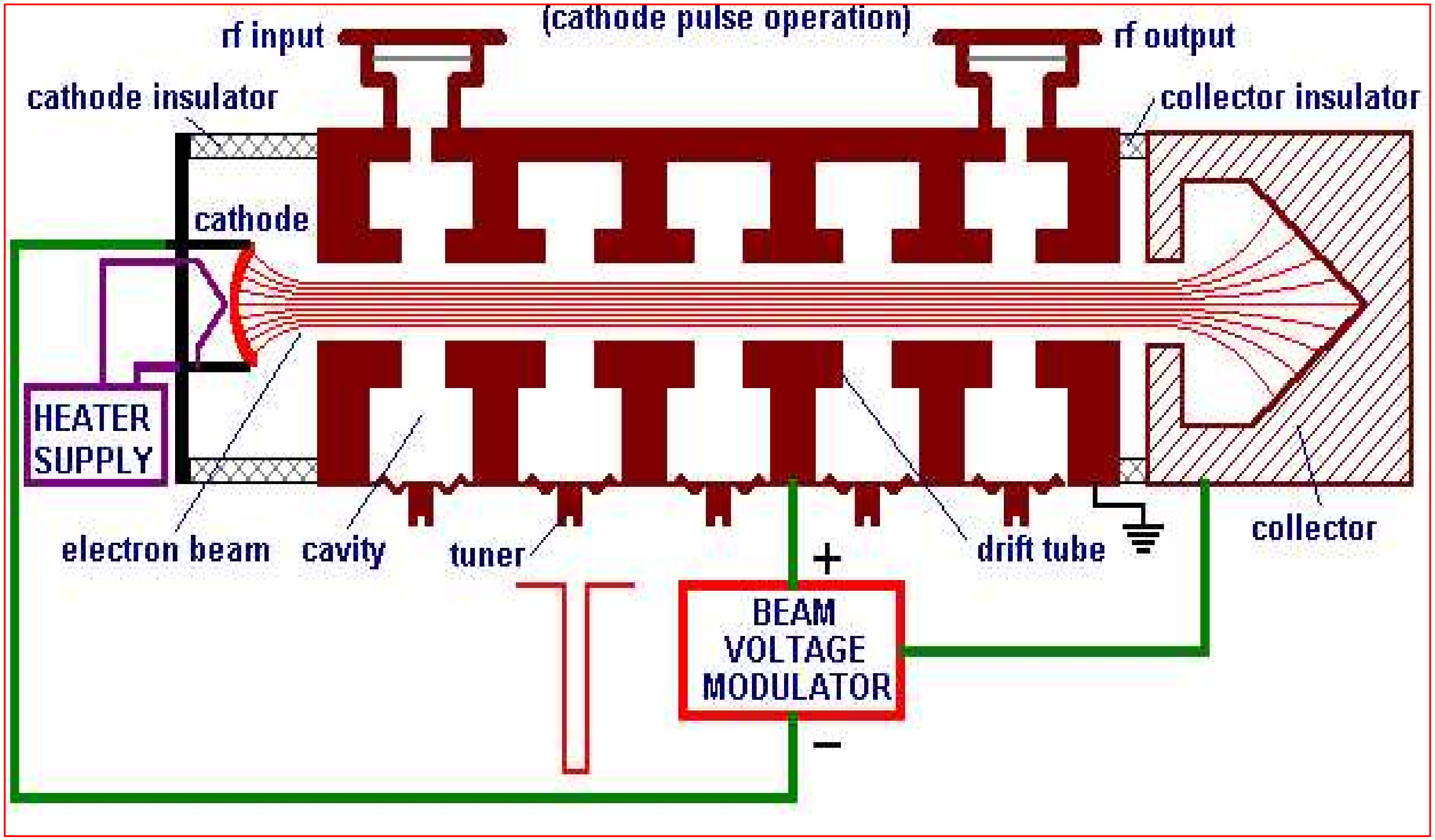
Why use Wave guide?

- Wave guide transmission line:
  - has a limited transmission bandwidth which is dependent on the wave guide dimensions.
  - lower the frequency, the larger the wave guide.
  - power handling capabilities are better c.f. coax, at high frequency.

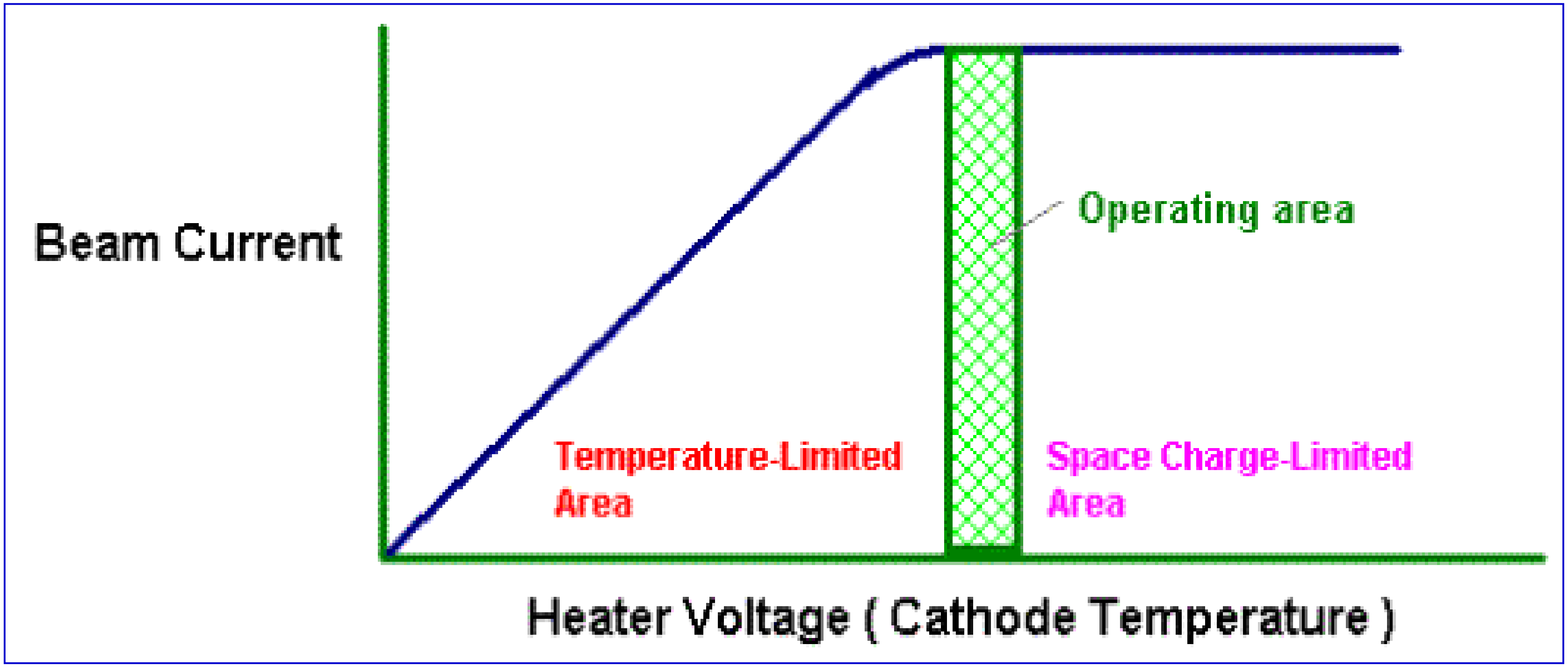
Wave guide vs. Coaxial

- Attenuation is comparable.
- At 352 MHz,
  – Wave guide has better power handling capability.
  – coaxial power capability is below APS requirements, even at large diameters (9 3/16”).
- ∴ Wave guide is the best choice.

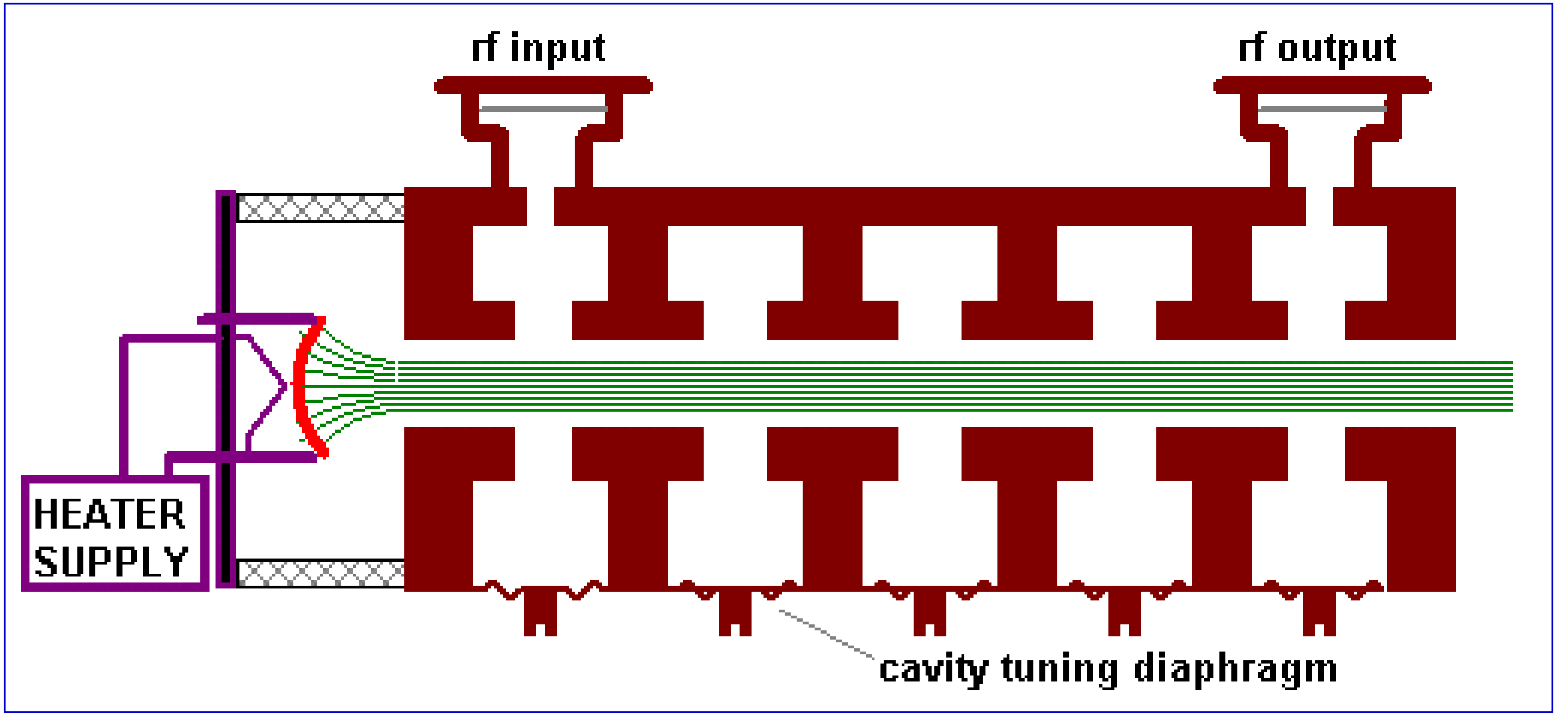
Klystron


(cathode pulse operation)
rf input
rf output
cathode insulator
collector insulator
cathode
HEATER SUPPLY
electron beam
cavity
tuner
drift tube
collector
+
BEAM VOLTAGE MODULATOR
–

Beam Current



Klystron: Cavities



Higher Order Modes (HOMs)

- Cavity geometry dictates the e-m field distribution.
- Cavity will not only resonate at the desired fundamental frequency, but also at other higher order frequencies.
- These HOM's can only be excited in the cavity **if** the beam contains that frequency.

Instabilities

- Main types of beam instability:
  - Robinson (longitudinal + transverse)
  - Coupled-bunch (longitudinal + transverse)
  - Microwave (longitudinal only)
  - Head-tail (longitudinal + transverse)
  - Negative Mass (longitudinal only)

Robinson
Coupled-bunch

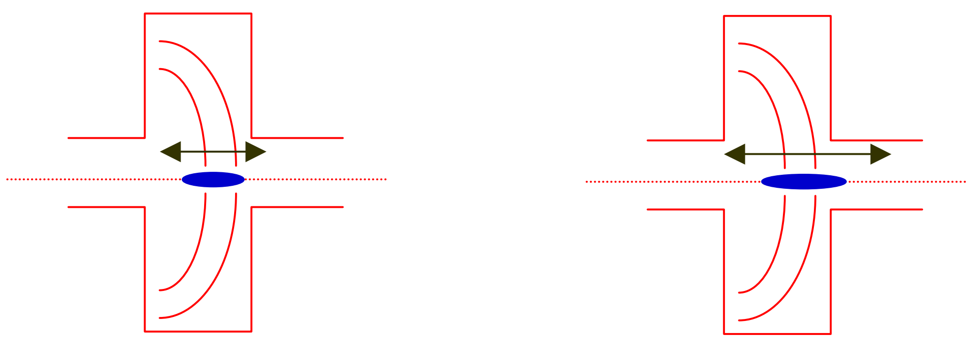
Head-tail

Microwave
Negative Mass

Macro-particle type ⟷ Internal motion in a bunch

Robinson Instability

- The most basic instability.
- A growing oscillation (long and/or trans) of a beam as a whole, when it interacts with an impedance source.



Coupled Bunch Instability (CBI)

- If there is more than one bunch (M bunches) in a ring:
  - Robinson instabilities may be coupled (synchronised) and the whole bunches may oscillate together in a certain pattern.
- When they are coupled:
  - M independent oscillation patterns.
  - Equal oscillation amplitude for all bunches
- CBIs driven by cavity HOMs.

Combating HOMs

- Elimination at the design stage
- Feedback systems
- Temperature control
- Harmonic separation of cavities
- Gapped beam
- Damping wigglers

Cavity HOM Dampers

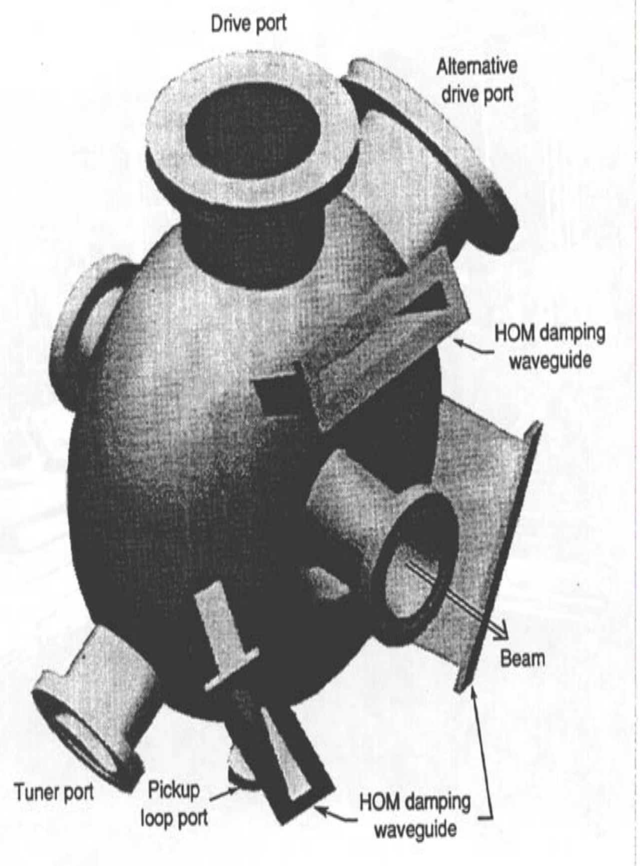


Fig. 5-95. Low-power test model of prototype PEP-II RF cavity.

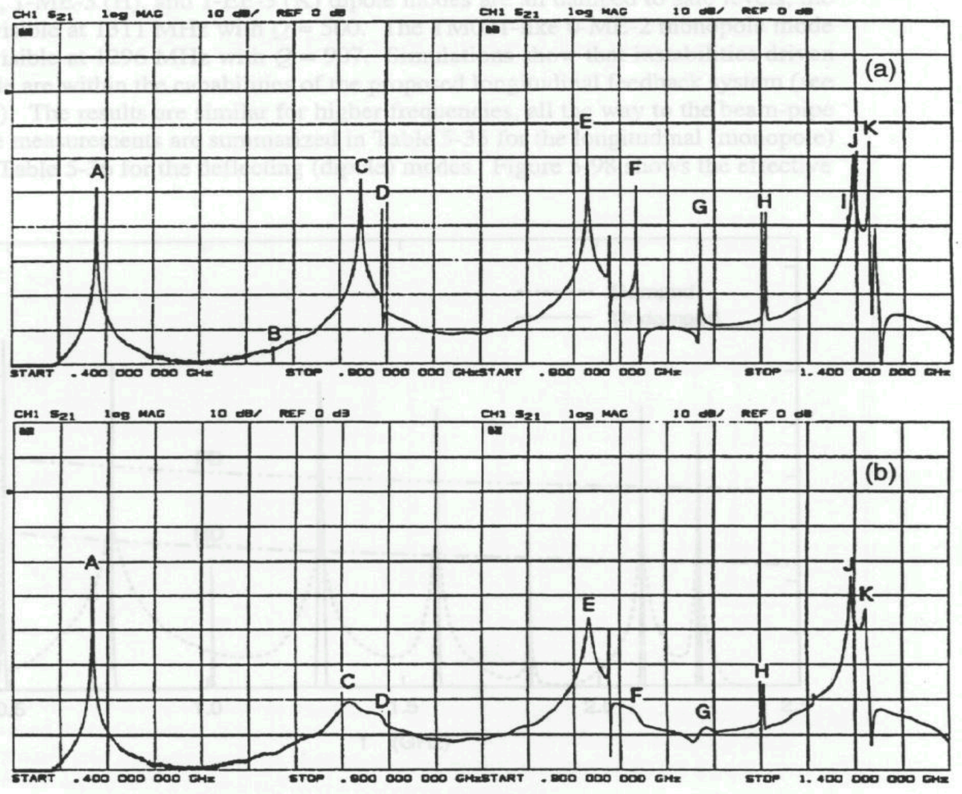
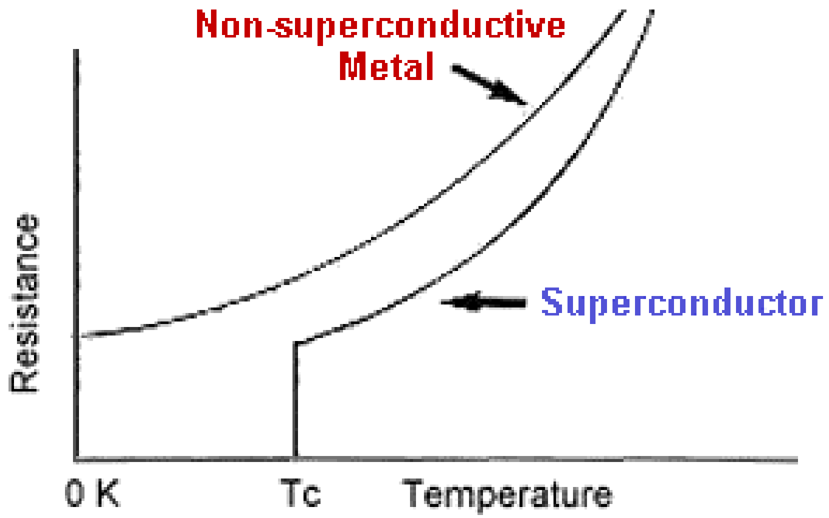


Fig. 5-97. Modes measured in the low-power test cavity from 0.4–1.4 GHz, (a) without damping, (b) with three damping waveguides. (Labels refer to modes in Tables 5-35 and 5-36).

Super conducting Technology

Superconductivity

Superconductivity is a phenomenon observed in several metals and ceramic materials. When these materials are cooled to temperatures ranging from near absolute zero (0 degrees Kelvin, -273 degrees Celsius) to liquid nitrogen temperatures (77 K, -196 C), their electrical resistance drops with a jump down to zero.



The temperature at which electrical resistance is zero is called the **critical temperature** (T_c)

Superconductivity

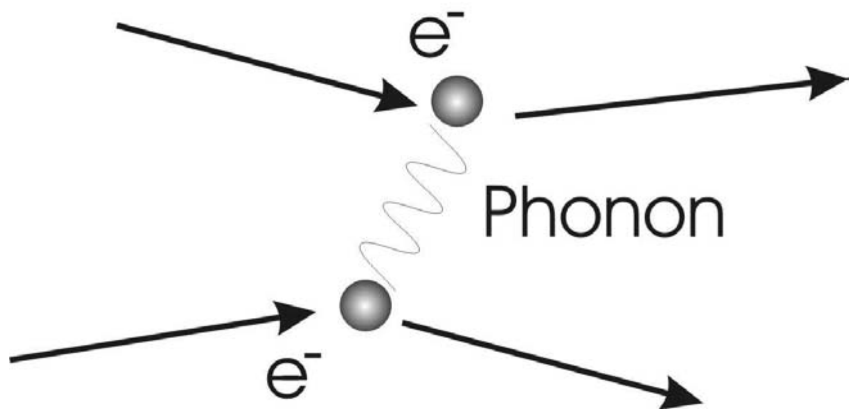
Some background .....

Electrical resistance in metals arises because electrons moving through the metal are scattered due to deviations from translational symmetry. These are produced either by impurities, giving raise to a temperature independent contribution to the resistance, or by the vibrations of the lattice in the metal.

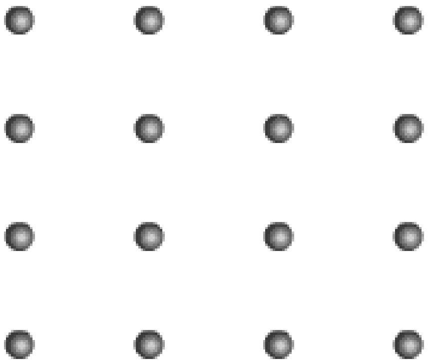
In a superconductor below its critical temperature, there is no resistance because these scattering mechanisms are unable to impede the motion of the current carriers. As a negatively-charged electron moves through the space between two rows of positively-charged atoms, it pulls inward on the atoms of the lattice. This distortion attracts a second electron to move in behind it.

An electron in the lattice can interact with another electron by exchanging an acoustic quanta called phonon. Phonons in acoustics are analogous to photons in electromagnetic. The energy of a phonon is usually less than 0.1 eV (electron-volt) and thus is one or two orders of magnitude less than that of a photon.

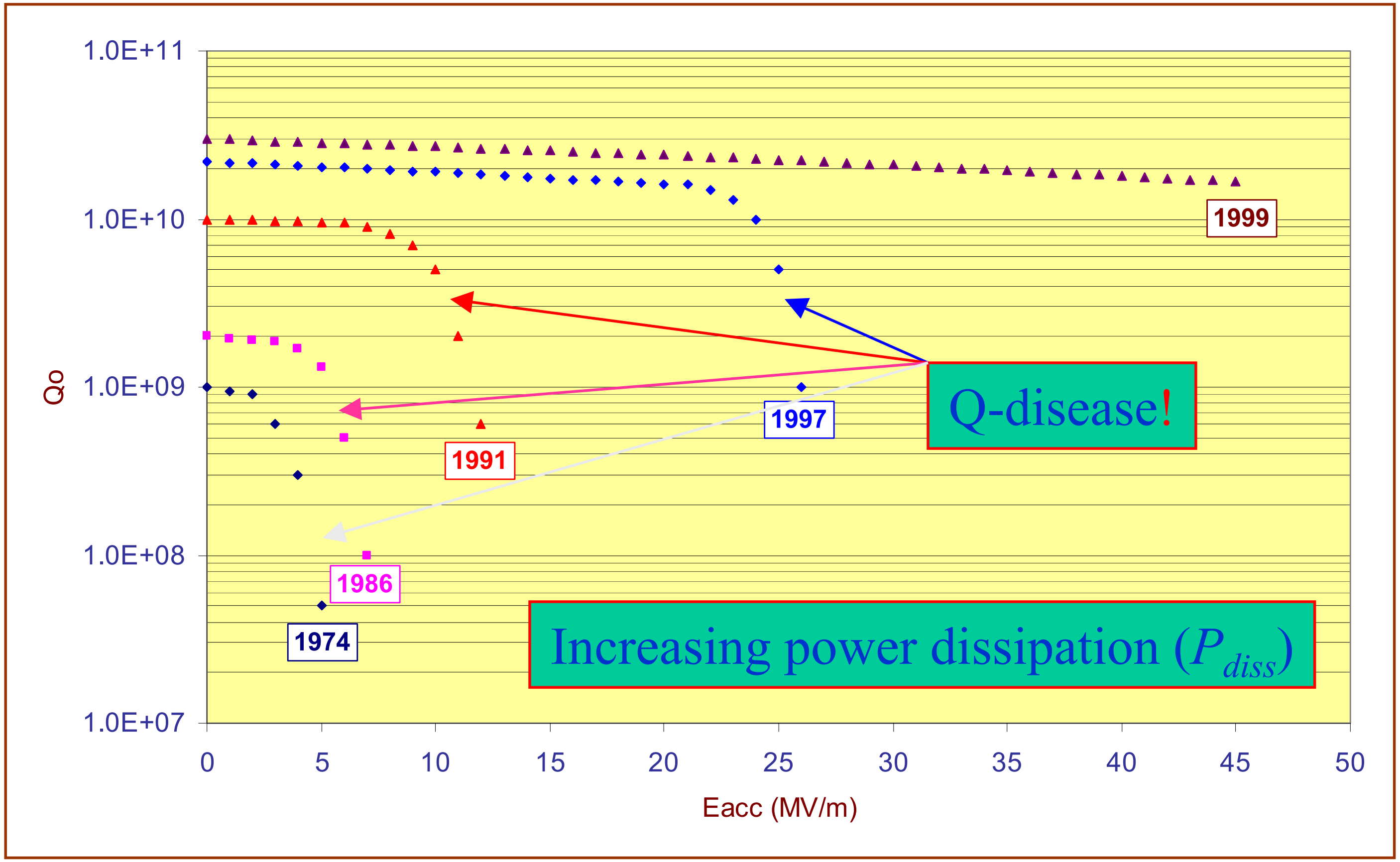
Superconductivity



The two electrons form a weak attraction, travel together in a pair and encounter less resistance overall. In a superconductor, electron pairs are constantly forming, breaking and reforming, but the overall effect is that electrons flow with little or no resistance. The current is carried then by electrons moving in pairs called Cooper pairs.



Performance History



Cavity Q-Factor (Q_o)

- The Q-factor is an important figure of merit for accelerating structures.

$$\boxed{Q_o = \frac{\omega_o U}{P_{diss}}}$$

Relates the stored energy (U) in a structure against the energy lost per RF period (P_{diss}).

Cavity Q-Factor (Q_o)

Total energy in the cavity defined as:

$$U = \frac{1}{2}\mu_o \int_V |H|^2 dv = \frac{1}{2}\varepsilon_o \int_V |E|^2 dv$$

Furthermore:

$$P_{diss} = \frac{1}{2} R_s \int_S |H|^2 ds$$

R_s = Surface Resistance (Ω)

Hence:

$$Q_o = \frac{\varpi_o \mu_o \int_V |H|^2 dv}{R_s \int_S |H|^2 ds}$$

Geometry Factor (G)

- Q_o can then be written as:

$$\boxed{Q_o = \frac{G}{R_s}} \quad \text{or} \quad \boxed{G = Q_o R_s}$$

- G depends on the cavity shape and not its size.
- Very useful for comparing different cavity shapes, irrespective of their size and wall materials.

Note:
The Q-factor does vary with cavity size, owing to the frequency dependence of R_s.

Shunt Impedance (R_o)

- Ideally want the R_o to be large for the accelerating mode, so that P_{diss} is minimised.

$$\boxed{R_o = \frac{V_{acc}^2}{2P_{diss}}}$$

- Particularly important for copper cavities, as wall dissipation is major issue.
- Can now relate R_o to Q_o.

R_o/Q_o

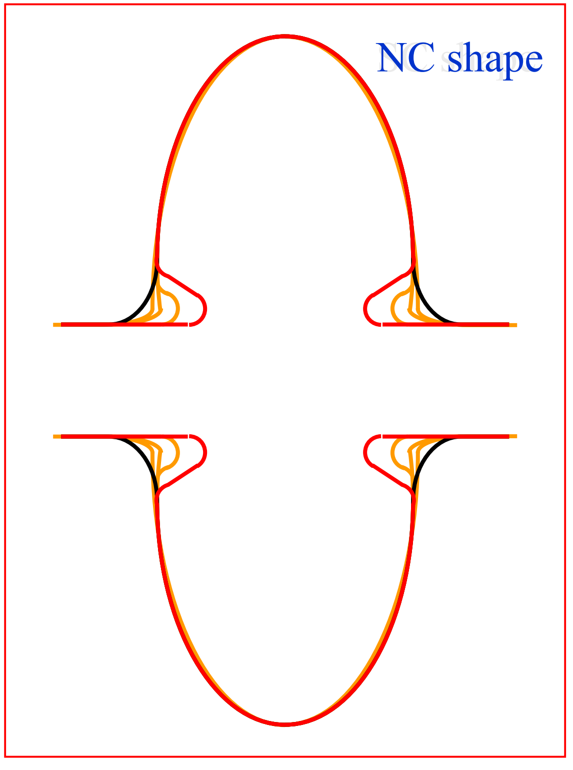
- Taking the ratio gives:

$$\boxed{\frac{R_o}{Q_o} = \frac{V_{acc}^2}{\omega_o U}}$$

- Which is independent of both the cavity shape and also R_s.
- In NC cavities, the R_o/Q_o is maximised by using a small beam tube.

R_o/Q_o

- R_o/Q_o further enhanced by making geometry re-entrant.



Lowers the H-field in the equator region $\Rightarrow$ reduced P_{diss}

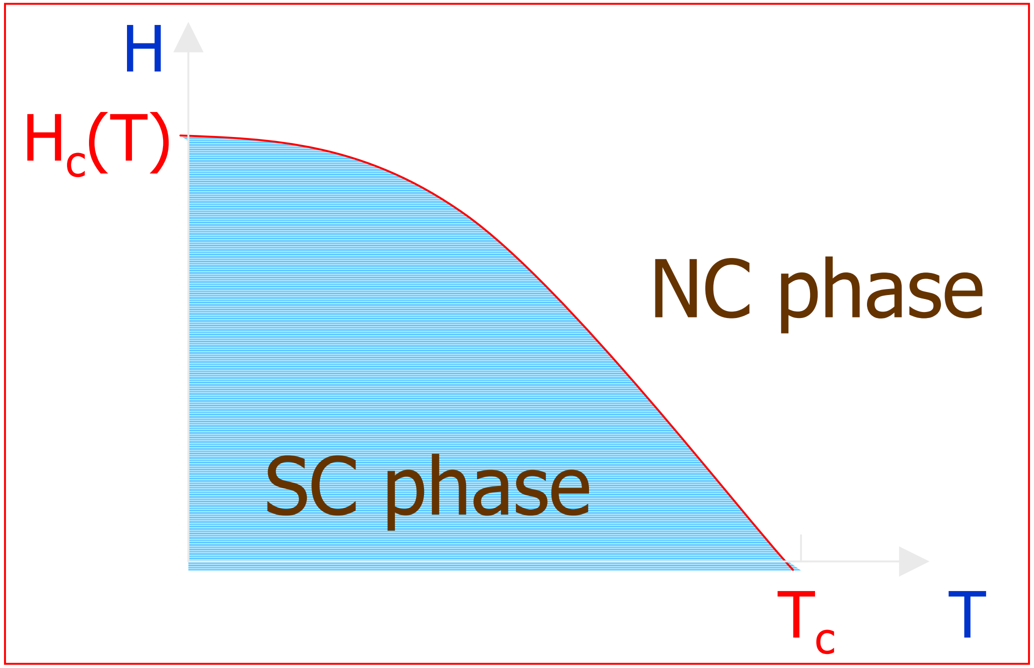
Remember: $$R_o = \frac{V_{acc}^2}{2P_{diss}}$$

HOM R_o/Q_o

- R_o/Q_o also increased for HOMs.
  - beam interacts more strongly with HOMs.
  - degrading beam quality + maximum possible charge/bunch.
- For SC cavities:
  - R_s~100,000 times less than NC.
  - P_{diss} no longer a major issue.
  - $\therefore$ can have large beam tubes.
  - reduced HOM R_o/Q_o is a big advantage!

SRF Fundamentals

- Nb is the material of choice for SC cavities, as it has the highest T_c of all pure metals.



Surface Resistance R_s

- SC process ⇒ condensation of charge carriers into Cooper Pairs.
- At T=0K, all charge carriers are condensed (SC).
- At $0 > T < T_c$ most carriers are paired, fraction are unpaired.
- At $T=T_c$, no carriers are paired (NC).
- Pairs move frictionlessly through material.
- Defined as London Two Fluid Model.

Surface Resistance R_s

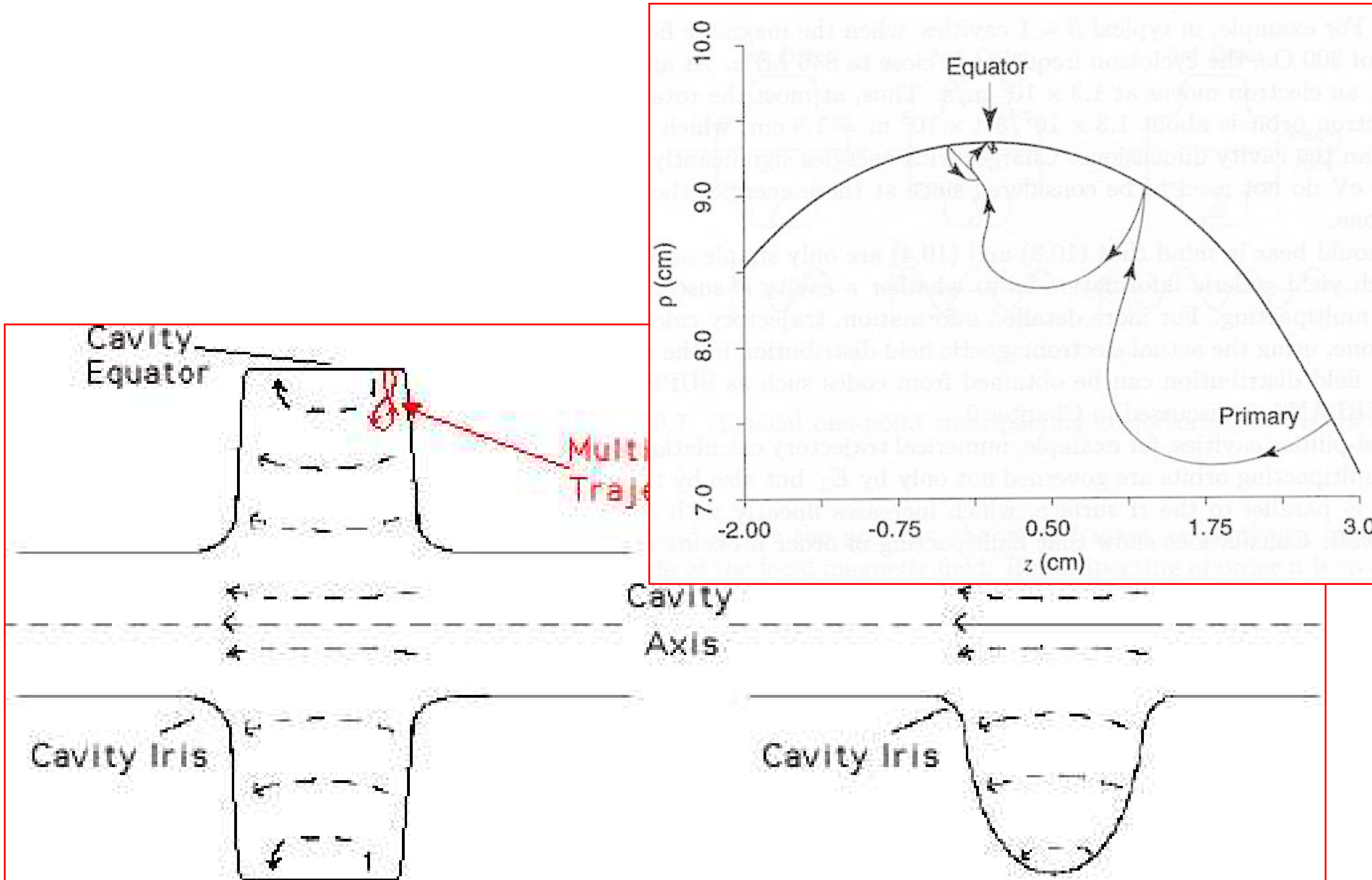
- DC fields:
  - at $T<T_c$, pairs carry all the current.
  - electrical resistance vanishes, $R_s=0\Omega$.
- RF fields:
  - dissipation does occur for $0 > T < T_c$.
  - albeit very small c.f. NC state, $R_s<10n\Omega$.
  - for RF currents to flow, RF fields penetrate into material wall by skin depth δ:

$$\delta = \frac{1}{\sqrt{\pi f \mu_o \sigma}}$$

Multipacting

- Early limitation $\Rightarrow$ e^- emitted from the RF surface follows trajectory and impacts back on the surface a number of RF cycles after emission; Resonant process.
- Impacting e^- frees further e^- which repeat the cycle $\Rightarrow$ *Avalanche* condition
- Cure, make cavity geometry elliptical, forcing ejected e^- to equator and minimum E-field.

Multipacting



Thermal Breakdown

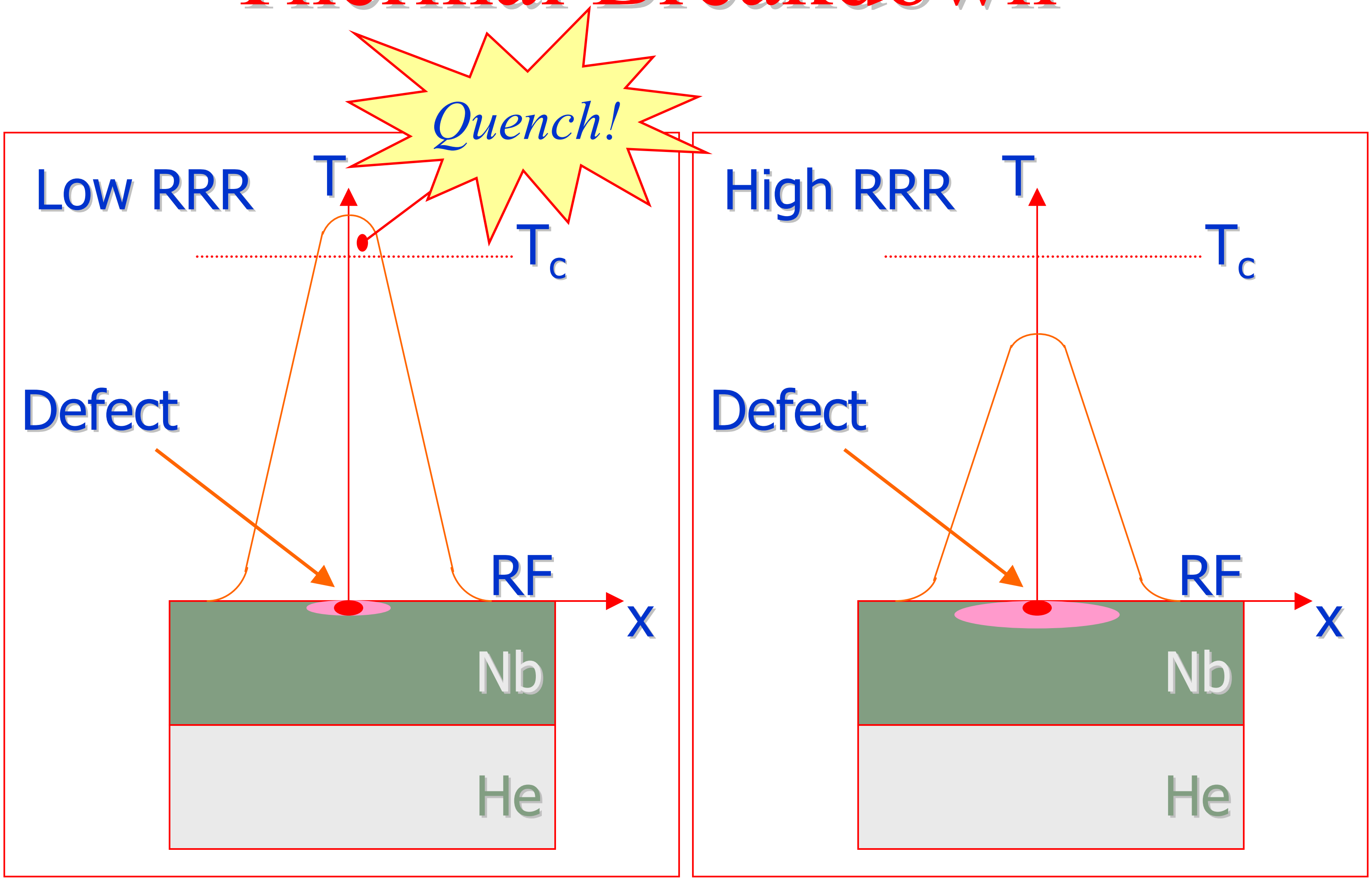
- Temperature of part (or all) of surface exceeds T_c, dissipating all stored energy.
- Localised effect $\Rightarrow$ surface defect has higher R_s.
- Quench occurs when surrounding material cannot dissipate the increased thermal load.
- High RRR $\Rightarrow$ less defects or higher purity.

(RRR $\equiv$Residual Resistivity Ration)

Ratio of bulk resistivity at room temperature to NC resistivity at 4.2K

A measure of purity and thermal conductivity of the niobium

Thermal Breakdown



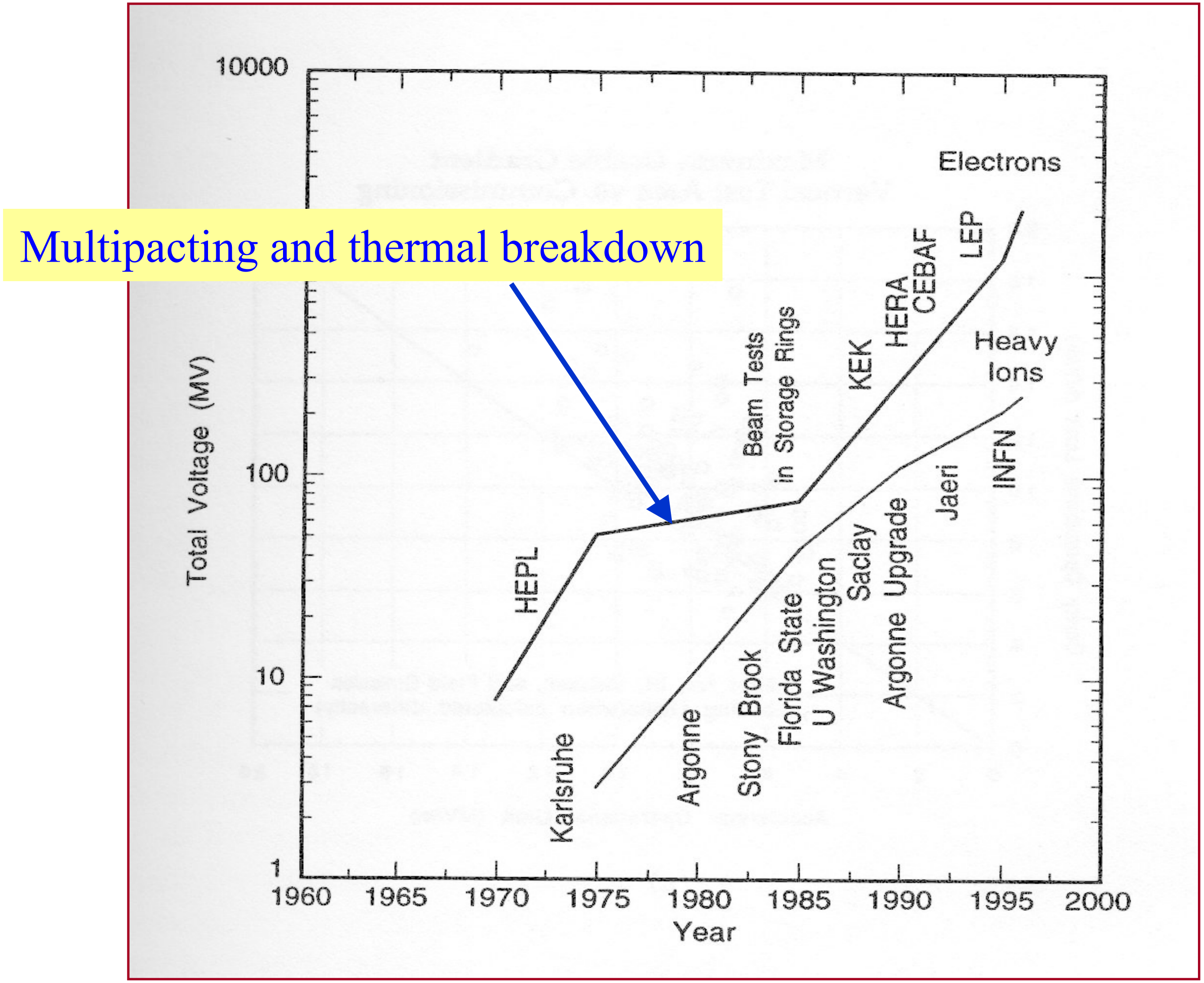
Advantages of SRF

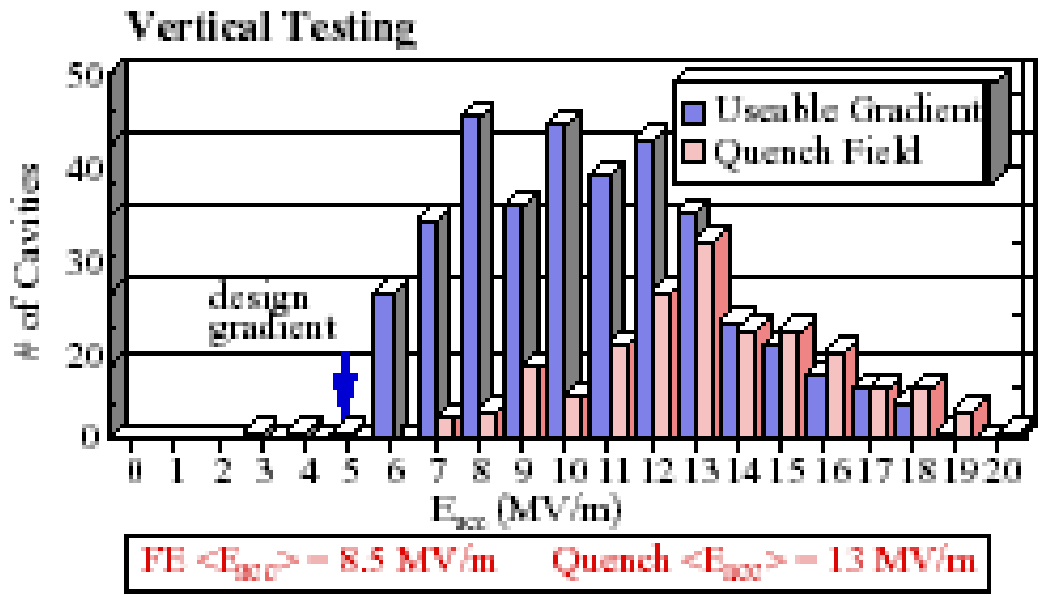
- Improved beam quality c.f. NC technology:
  - P_{diss} is much less, as R_s ~10^5 lower.
  - Higher E_{acc} for less power $\Rightarrow$ more efficient.
  - Significantly better HOM damping.
  - Reduced cavity-beam interaction:
    - larger beam tubes.
    - don't need as many accelerating cells.

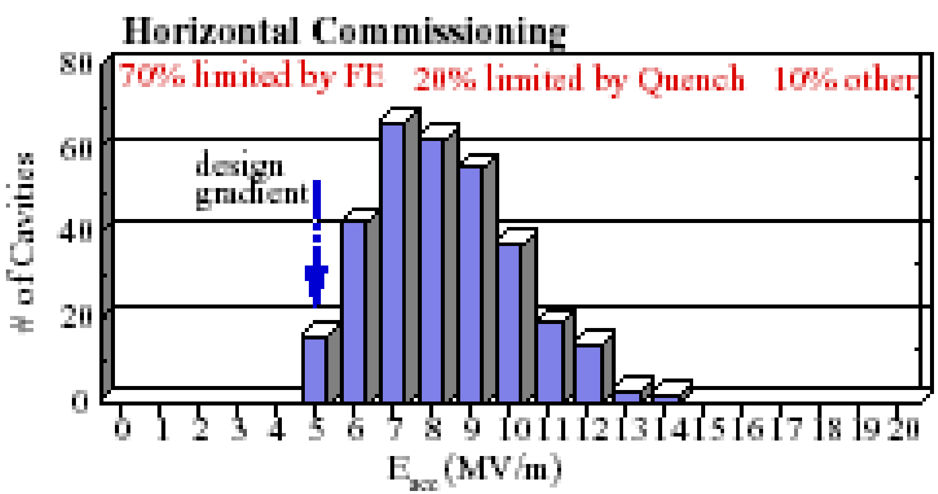
However .....

- Cavities require refrigerator cooling:
  - total power saving does not reflect $\sim 10^5$.
  - more like 10^3, when include fridge efficiency.
- Beam loading of SC cavity:
  - requires more stringent control of cavity phase and amplitude.
  - microphonics due to high E_{acc}.

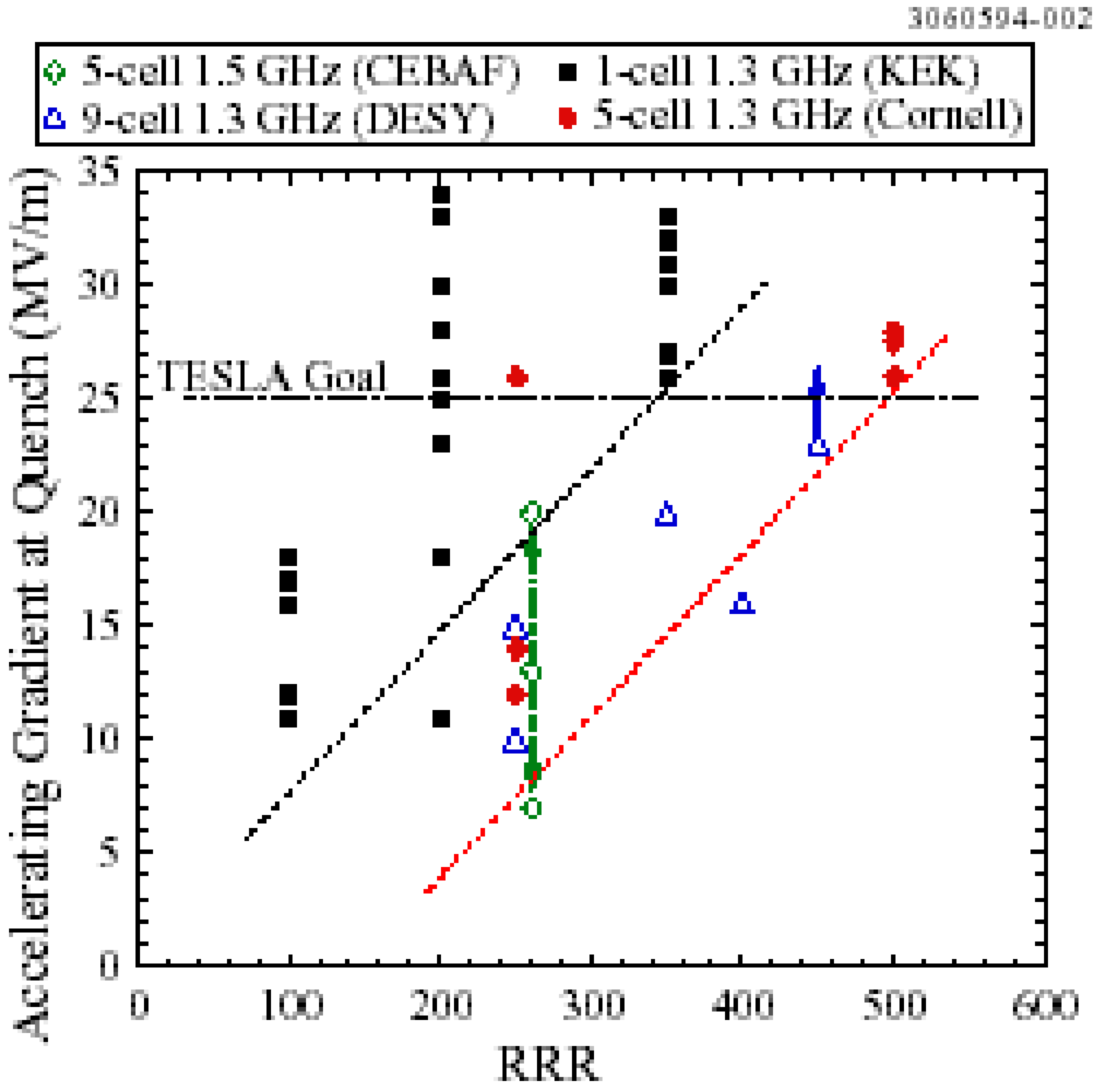
SRF Voltage Trend



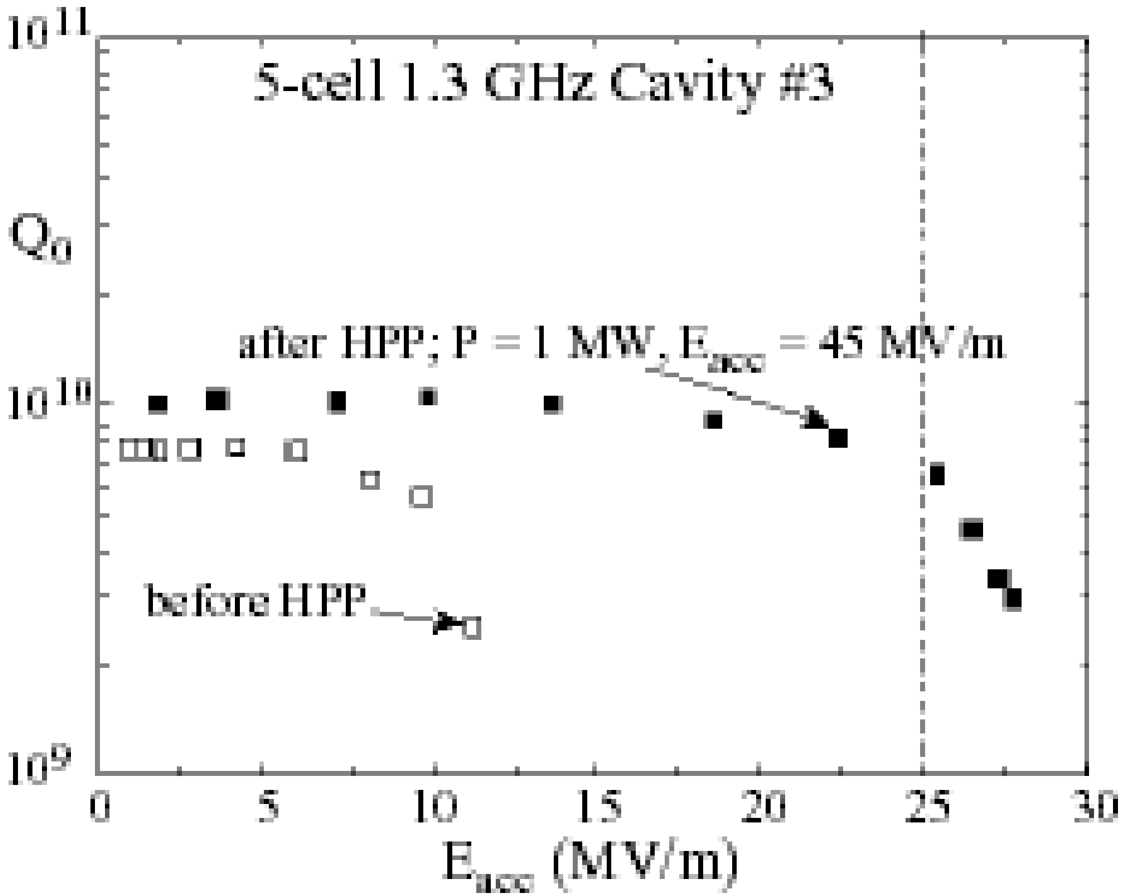

Vertical Testing
Usable Gradient
Quench Field
design gradient
# of Cavities
E_acc (MV/m)
FE <E_acc> = 8.5 MV/m
Quench <E_acc> = 13 MV/m


Horizontal Commissioning
70% limited by FE
20% limited by Quench
10% other
design gradient
# of Cavities
E_acc (MV/m)

Accelerating Gradient

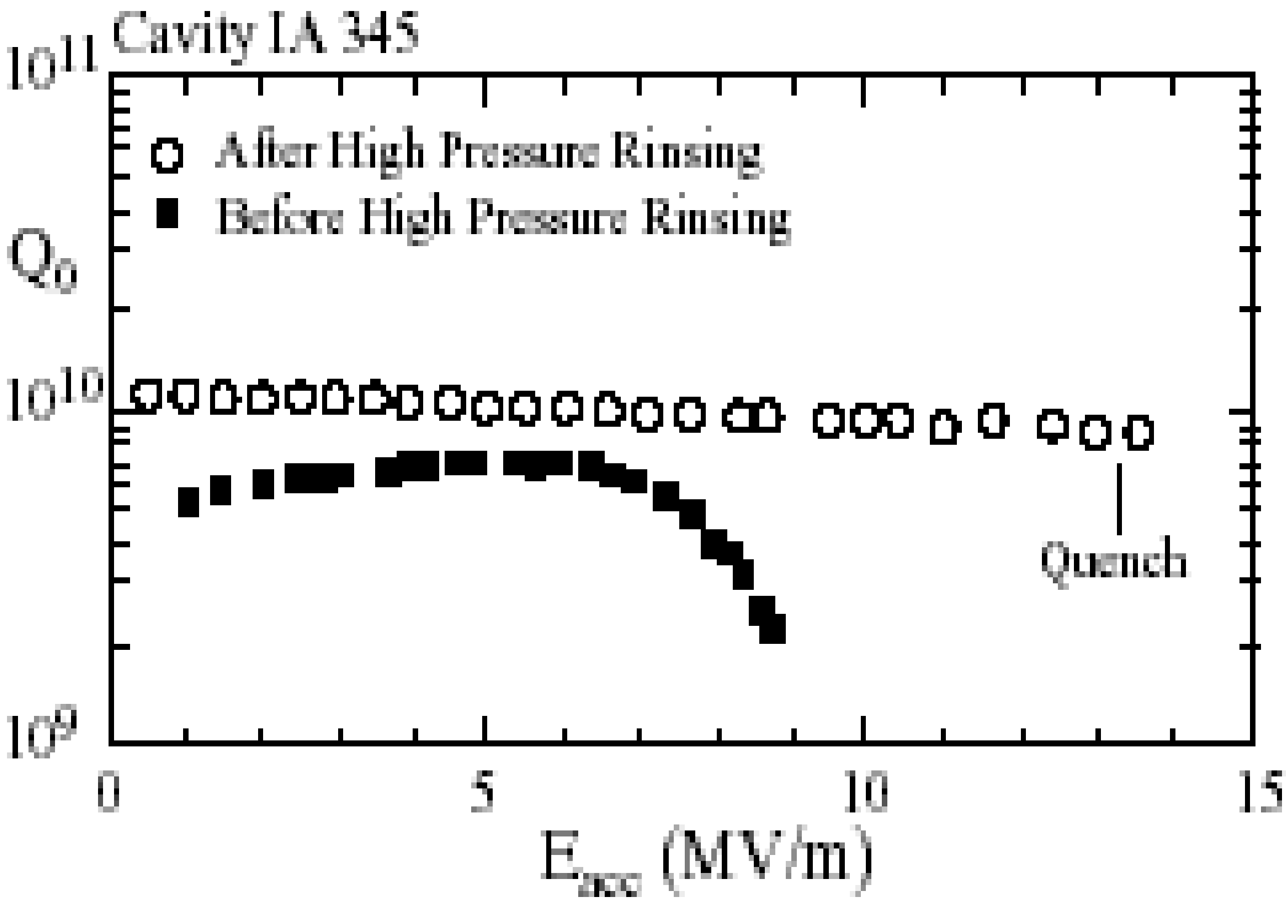


Q vs. E_{acc} (High Power Processing)

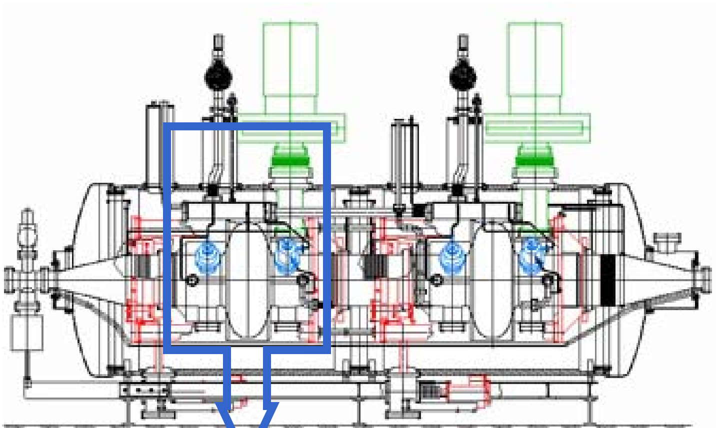


5-cell 1.3 GHz cavity at Cornell

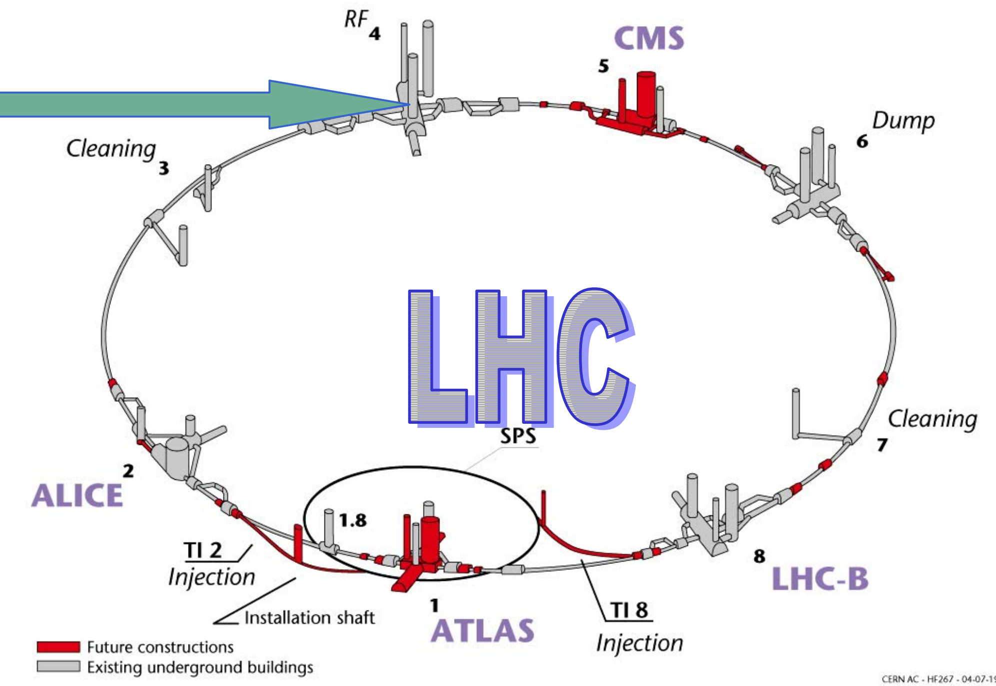
Q vs. E_{acc} (High Power Processing)

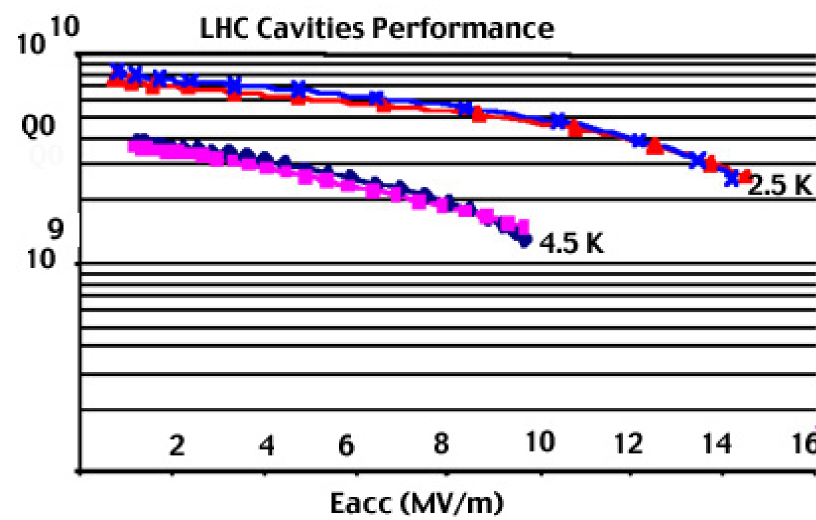


5-cell 1.5 GHz cavity at CEBAF (JLAB)



Layout of the LEP tunnel including future LHC infrastructures.



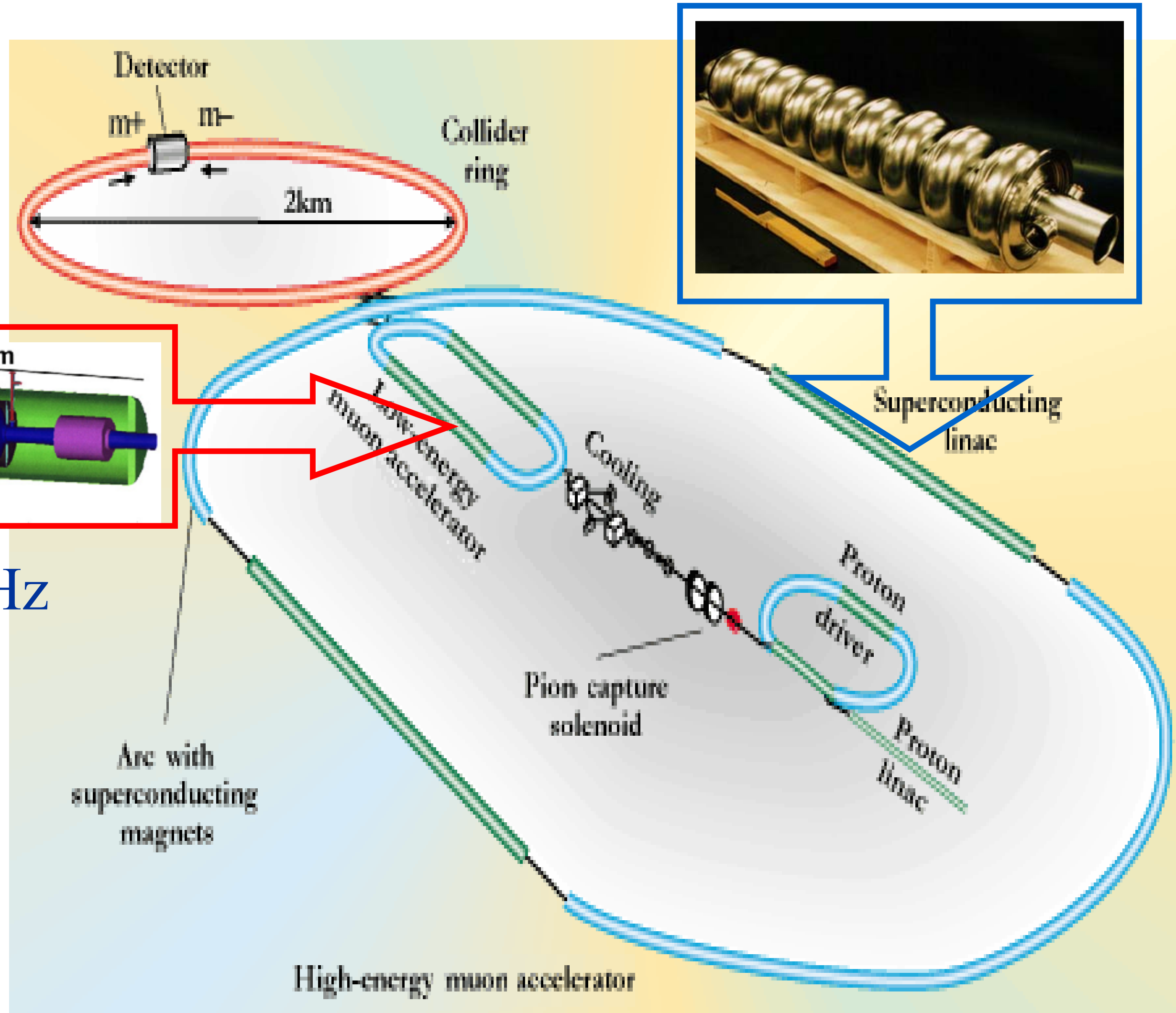


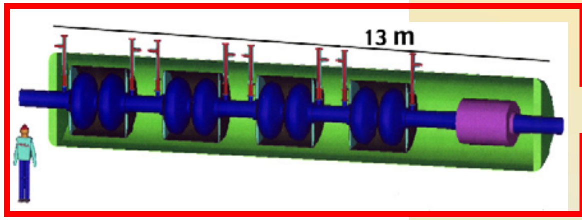
400 MHz

16 Nb/Cu Cavities

Future Muon Collider

1300 MHz

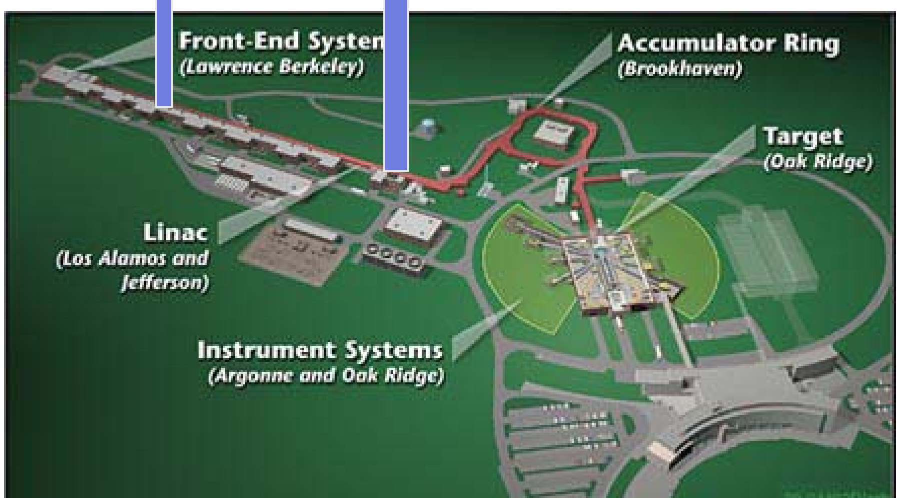




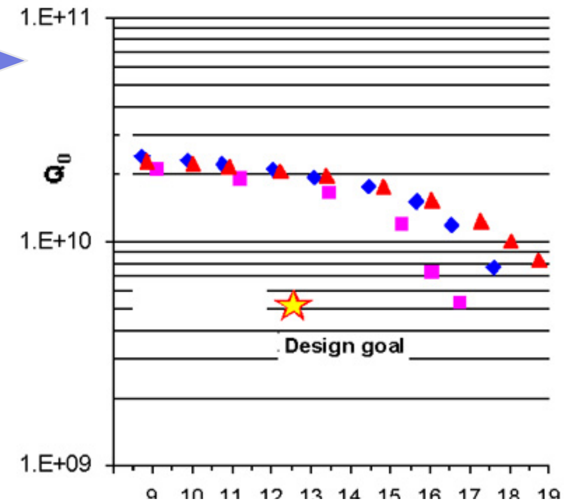
200 - 400 MHz

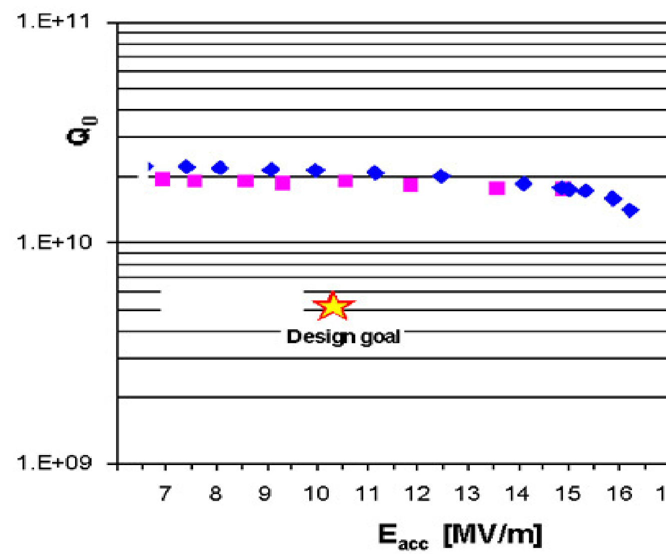
SNS Goes Superconducting

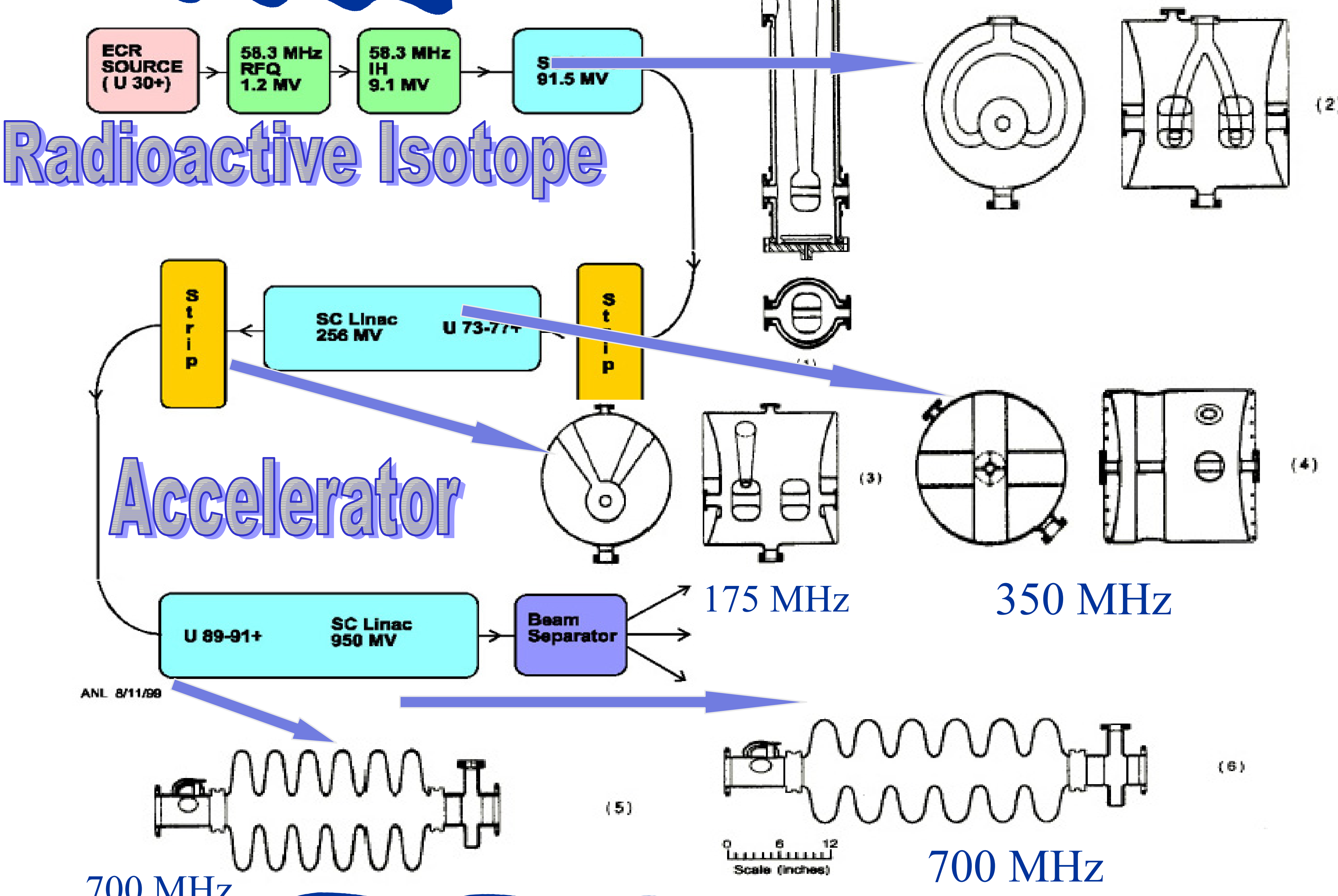
Beta = 0.6



800 MHz






58 MHz
117 MHz
ECR SOURCE (U 30+)
58.3 MHz RFQ 1.2 MV
58.3 MHz IH 9.1 MV
91.5 MV
(2)
Radioactive Isotope
SC Linac 256 MV
U 73-77+
Strip
Strip
(3)
(4)
Accelerator
175 MHz
350 MHz
U 89-91+
SC Linac 950 MV
Beam Separator
ANL 8/11/99
(5)
(6)
0 6 12
Scale (inches)
700 MHz
700 MHz

Conclusions

- SRF limitations are being overcome.
- SRF gradients increasing.
- Surface E-fields approaching fundamental limits are being achieved.
- SRF operational experience now available, CEBAF, CERN, Cornell, and KEKB.
- Installed SRF voltage around the world's accelerators is increasing exponentially!